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^{8}Be nuclear data evaluation

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Abstract

The final results for the R-matrix analysis of experimental nuclear data on the reactions $^{4}He(\alpha,\alpha)$, $^{4}He(\alpha,p)$, $^{4}He(\alpha,d)$, $^{7}Li(p,\alpha)$, $^{7}Li(p,p)$, $^{7}Li(p,n)$, $^{7}Be(n,p)$, $^{6}Li(d,\alpha)$, $^{6}Li(d,p)$, $^{6}Li(d,n)$ and $^{6}Li(d,d)$, leading to the ^{8}Be intermediate state, are presented. The excitation energy above the ^{8}Be ground state has been brought up to $25-26$ MeV for all reactions except $^{4}He(\alpha,\alpha)$ and $^{7}Be(n,p)$. The new data that were added to achieve this are discussed in detail. The data for the reactions $^{4}He(\alpha,\alpha)$ and $^{6}Li(d,d)$ do not fit well, but the other six reactions fit with a reasonable χ^2/(point). The possibility of eight units of orbital angular momentum between ^{4}He and α, three units between ^{7}Li and p, three units between ^{7}Be and n, and two units between ^{6}Li and d, was added. The parameters of the 19 resonances needed for the analysis are given. Most of these correspond to resonances formerly known from experiment. Evaluated $^{4}He(\alpha,p)$, $^{4}He(\alpha,d)$, $^{7}Li(p,\alpha)$, $^{7}Li(p,n)$, $^{6}Li(d,\alpha)$, $^{6}Li(d,p)$ and $^{6}Li(d,n)$ cross-sections are presented. Evaluated cross-section files in ENDF format were prepared for the twelve reactions $p\,^{7}Li,\ n\,^{7}Be,\ d\,^{6}Li \to \alpha\,^{4}He,\ p\,^{7}Li,\ n\,^{7}Be,\ d\,^{6}Li$. Maxwellian averaged cross-sections in NDI format were prepared for the six reactions $^{7}Li(p,\alpha)$, $^{7}Li(p,n)$, $^{7}Be(n,p)$, $^{6}Li(d,\alpha)$, $^{6}Li(d,p)$ and $^{6}Li(d,n)$.

1 Strategy for data inclusion

One of the advantages of analyzing nuclear data with the R-matrix formalism is that it provides a constraint between various nuclear reactions called unitarity [1]. The analysis of

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the ^8Be system as it stood in 2002 did not fully utilize this constraint. As indicated in Table 1, the former analysis amounted to partitioning the problem into three separate blocks, which did not constrain the others via unitarity. These blocks were the $^4He(\alpha,\alpha)$ channel, the $^4He(\alpha,p)$, $^7Li(p,\alpha)$, $^7Li(p,p)$, $^7Li(p,n)$ and $^7Be(n,p)$ channels, and the $^6Li(d,\alpha)$, $^6Li(d,p)$ and $^6Li(d,n)$ channels. In the 2004 analysis all three blocks constrain each other via unitarity.

There are 16 different reactions for which cross-sections can be obtained via this analysis. These are $\alpha\,^4He$, $p\,^7Li$, $n\,^7Be$, $d\,^6Li \rightarrow \alpha\,^4He$, $p\,^7Li$, $n\,^7Be$, $d\,^6Li$. In addition to unitarity, constraints between reactions are also provided by time-reversal symmetry (i.e. when the initial and final particles are interchanged), and isospin symmetry [1]. For example, no data were entered for $^4He(\alpha,n)$, $^7Li(p,d)$, $^7Be(n,\alpha)$, $^7Be(n,n)$ and $^7Be(n,d)$; and only very low energy data for $^7Be(n,p)$. However, three of these reactions are strongly constrained via their time-reverse reactions [$^7Li(p,d)$, $^7Be(n,d)$ and $^7Be(n,p)$]. Moreover, the other three reactions are constrained by isospin symmetry [$^4He(\alpha,n)$ is constrained by $^4He(\alpha,p)$, $^7Be(n,\alpha)$ by $^7Li(p,\alpha)$, and $^7Be(n,n)$ by $^7Li(p,n)$].

The new maximum laboratory energies for the incoming projectile are listed in Table 1. All reactions where data were entered, except $^4He(\alpha,\alpha)$ and $^7Be(n,p)$, include data up to an excitation energy of $25-26$ MeV in the current analysis. In the $^4He(\alpha,\alpha)$ reaction, data above the indicated maximum α laboratory energy and below the limit of this analysis (52 MeV laboratory energy), are only available as phase shifts [2], and have not been incorporated. For the $^7Be(n,p)$ reaction no data above the previous maximum laboratory energy were found below the maximum excitation energy of this analysis (26 MeV). For the reactions $^4He(\alpha,p)$ and $^4He(\alpha,d)$, no higher energy data than those entered are known to be available up to the limit of this analysis (52 MeV α laboratory energy).

2 New data included

2.1 $^4He(\alpha,\alpha)$

Bredin 1959 [3]: Previously data from $23.1-34.2$ MeV were entered from Ref. [3]. In this analysis the data from $35.1-38.4$ MeV were entered.

Relative error: The errors in Table 2 (p. 149 [3]) which were entered into the datafile only includes statistical errors: "The uncertainties listed with the individual cross sections are purely statistical." (p. 150 [3])

Normalization error: There are two sources of errors beyond the relative errors mentioned: (a) There is an additional systematic uncertainty: "Within each angular distribution there is a possibility of small systematic errors in the relative cross sections, but these should not reach 5% even at the smallest angle used." (p. 150 [3]) (b) There are large errors in

Reaction	2002 analysis			2004 analysis			
	E_{max}	E_X	Below Threshold	E_{max}	E_X	Below Thr.	Data
$^4He(\alpha,\alpha)$	34.2	17.0	$p\,^7Li,\ n\,^7Be,\ d\,^6Li$	38.4	19.2	$d\,^6Li$	1066
$^4He(\alpha,p)$	42.6	21.2	$d\,^6Li$	49.5	24.7		58
$^4He(\alpha,d)$	-			49.5	24.7		3
$^7Li(p,\alpha)$	1.8	18.8	$d\,^6Li$	10.1	26.1		255
$^7Li(p,p)$	3.0	19.9	$d\,^6Li$	10.3	26.3		1550
$^7Li(p,n)$	3.0	19.9	$d\,^6Li$	10.0	26.0		828
$^7Be(n,p)$	0.0	18.9	$d\,^6Li$	0.0	18.9	$d\,^6Li$	208
$^6Li(d,\alpha)$	1.5	23.4		5.0	26.0		401
$^6Li(d,p)$	1.0	23.1		5.0	26.0		670
$^6Li(d,n)$	1.5	23.4		3.7	25.1		156
$^6Li(d,d)$	-			5.0	26.0		54

Table 1: Comparison of the 2002 and 2004 analyses. The maximum laboratory energy E_{max} of the incoming projectile in MeV that was used, as well as the corresponding excitation energy E_X above the ^8Be ground state in MeV, are indicated. The number of data points is also indicated. The data for $^7Be(n,p)$ are at very small energies. No data were entered for $^4He(\alpha,d)$ and $^6Li(d,d)$ in the 2002 analysis.

the angle measurements: "The c.m.s. angles listed are accurate to $\pm 0.8^o$, with a resolution about 0.8^o at 30^o and 2.0^o at 90^o." (p. 149 [3]). A glance at the table makes it clear that these angle uncertainties can cause large uncertainties in the cross section (up to about 30%). The combined error from (a) and (b) above is estimated to be 10%. This error was added independently to the normalization error mentioned below to obtain a "total" normalization error, although the errors in (a) and (b) above should rigorously be taken into account on a data point by data point basis. The energy normalization error has a smaller influence on the cross sections and is neglected: "The accuracy of the determinations of beam energy was estimated to be ± 0.3 MeV or better in all exposures." (p. 148 [3]). The normalization error in Table 1 (p. 149 [3]) is added: "The uncertainty in the absolute scale of the whole angular distribution for each energy is also listed: this uncertainty arises principally from the measurement of total beam charge, or from normalization by means of the excitation function." (p. 150 [3]).

The data were measured for each energy as a function of angle: "For each exposure a value for the energy of the beam particles was obtained from the mean range of the scattered particles at each angles." (p. 146 [3]). See also Figs. 4 (b) - (d) where differential cross sections as a function of angle are plotted. Hence a different normalization should be allowed for each energy.

2.2 $^4He(\alpha, p)$

King 1977 [4]: Integrated data is available in the range 38.97 − 49.49 MeV (11 energies) in Table 1 (p. 1713 [4]), of which the data from 38.97 − 49.49 MeV were entered. Cross sections to ground and excited ^7Be product states are clearly separated.

Relative error: The errors quoted includes both statistical errors, which are very small, and systematic errors: "The uncertainties shown . . . of the integral cross section are total uncertainties, containing not only statistical contributions, but also systematic uncertainties in the determination of the detector collimator geometry, in the temperature and the pressure of the target gas, in the integrated beam current, and in the detector angle. All these uncertainties were added in quadrature and typically amount to about 5%, with the statistical contributions usually negligible compared to the rest." [4]

Normalization error: There is no further source of normalization errors beyond the systematic errors already discussed, so the normalization is fixed to 1. For this reason all the energy points are chosen to have a common normalization, except for those where differential cross sections also exists (see below).

King 1977 [4]: Differential cross sections for three energies, Figure 2(a), p. 1714 [4], were entered. Cross sections to ground and excited ^7Be product states are clearly separated.

Relative error: The errors indicated in Figure 2(a) [4] are taken to be purely statistical, as they are much smaller than the combined errors quoted for the integrated cross sections (see above). These statistical and digitization errors are included in the datafile.

Normalization error: This is taken to be the same as the errors quoted for the integrated cross sections (above): 5.0%, 5.0% and 4.8% for the 39.80, 44.32 and 47.65 MeV data respectively. Different normalizations where chosen for each energy since angular distributions for specific energies were measured (see Fig. 2 [4]) Note that the integrated cross section (see above) and differential cross section for the *same* energy were taken to have the same normalizations, as the integrated data were determined from the angular data.

2.3 $^4He(\alpha, n)$

A search for data in this reaction below 52 MeV α laboratory energy, corresponding to the maximum excitation energy of this analysis, was made. The only relevant reference was Ref. [4], but it does not separate ground and excited product ^7Be states, so was not incorporated in the datafile.

2.4 $^4He(\alpha, d)$

King 1977 [4]: The data were entered. Cross-sections to ground ^6Li product states are clearly separated. Integrated data in the range 46.7-49.5 MeV (3 energies) in Fig. 6 (p. 1718) were entered. There is no error discussion. However, it is assumed that the errors are the same as for the $^4He(\alpha, p)$ reaction [4].

Relative error: The errors quoted include both statistical errors, which are very small, and systematic errors: "The uncertainties shown ... or the integral cross-section are total uncertainties, containing not only statistical contributions, but also systematic uncertainties in the determination of the detector collimator geometry, in the temperature and the pressure of the target gas, in the integrated beam current, and in the detector angle. All these uncertainties were added in quadrature and typically amount to about 5%, with the statistical contributions usually negligible compared to the rest." (p. 1713 [4])

Normalization error: There is no further source of normalization errors, so the normalization is fixed to 1.

2.5 $^7Li(p, \alpha)$

In this reaction a detailed analysis was made of the normalizations of data sets that were entered before 2002, because of an ambiguity of a factor of 1/2 in the cross-section due to identical particles in the final state. During this investigation information about normalization errors was also incorporated.

Spraker 2000 [5]: The data, which were entered previously, were reanalyzed.

Normalization error: The normalization is unmeasured: "The absolute scale shown here was obtained by normalizing the present results to those of Rolfs and Kavanagh." (p. 4 [5])

Harmon 1989 [6]: The data, which were entered previously, were reanalyzed.

Normalization error: The normalization is fixed to another reference, so that the normalization uncertainty is set to infinity: "The total cross-section for the $^7Li(p, \alpha)$ reaction reported here has been measured relative to the total cross-section of the $^6Li(p, \alpha)$ reaction at laboratory energies down to 20 keV." (p. 507 [6]) A factor of 1/2 was not included in the definition of the cross-section: "The data in table 1 and the coefficients in eq.(3) refer to the cross-section for alpha particle production per proton rather than reactions per proton. Consequently they must be divided by 2 in order to compare them with the results of Rolfs and Kavanagh." (p. 508 [6])

Rolfs 1986 [7]: The data, which were entered previously, were reanalyzed.

Normalization error: "Error ... does not include ..., but not the overall 8% error in the cross-section normalization" (p. 185 [7]); and "The errors given do not include an overall uncertainty of 8% in the absolute normalization." (p. 184 [7]) Hence the normalization error is set to 8%. A clear cross-section formula is stated and it is said that "The factor of 2 in the above relation takes into account that two α-particles are produced per reaction." (p. 185 [7]) This means that a factor of 1/2 was included in the definition of the cross-section.

Engstler 1992 [8]: The data, which were entered previously, were reanalyzed.

Normalization error: The data are the S-factor in Table 1 [8] converted to cross-section. The data include both the error quoted in Table 1 explicitly and the error quoted in the footnotes, which should be construed as a normalization error. In the light of this, there is no further need for an explicit normalization error. The normalization for a certain part of the data was determined in this work: "The absolute cross-sections $\sigma(E)$ were determined at the effective energies from $E = 32$ to 1004 keV (400 kV and 4 MV accelerators) using ..." (p. 478 [8]) The normalization for another part of the data was determined in a previous work: "... the absolute scales of the solid target data have been normalized to previous results using polynomial fits." (p. 480 [8]) It is explicit in Eq. 3 [8] that a factor of 1/2 was included in the cross-section definition.

Kilian 1969 [9]: The energy range of the data [9] is $2.7 - 10.6$ MeV at angles $40, 60, 70, 80,$ $90, 110, 120, 130,$ $140, 150, 160$ and 170 degrees. The differential cross-section data in Fig. 10 [9] was entered from $3.4 - 9.4$ MeV. Ground and excited state ^7Li products are well separated. The target is enriched ^7Li (99.99%).

Relative error: The data that was entered is said to have "Die Gröβe der Punkte entspricht den statistischen Fehlern." (p. 540 [9]) Hence the errors are as large as the points indicated. The size of the points was estimated and found to be in agreement with the EXFOR digitization error, and hence the EXFOR digitization was assigned to the relative error in the datafile. The normalizations should be different for each energy. This follows because measurements at the different angles were simultaneously made for a given energy: "Die Messungen wurden mit 16 Halbleiterzählern gleichzeitig durchgeführt, wobei folgende Streuwinkel θ_{Lab} bezetzt waren: ..." (p. 530 [9]).

Normalization error: "... wobei f [the overall normalization] die gemessenen Zählraten an einen absoluten Masβtab anpaβt. Zur Anpassung wurden Messungen im α-Kanal von Mani *et al.* und im Protonenkanal von Fasoli *et al.* benutzt." (p. 535-536 [9]). Consultation of Mani *et al.* [12] indicated that that reference also did not estimate its normalization, since it was also fixed to another reference. Based on this an infinite normalization error was assigned to the data [9].

Freeman 1958 [10]: The data were entered from Table 1 (p. 149) of that reference. This data go up to 1.5 MeV proton laboratory energy and the absolute cross-section was measured: "The cross-section for the $^7Li(p,\alpha)^4He$ reaction was calculated ..." (p. 149 [10]) There are no known absolute cross-section measurements in the energy region $1.6 - 11.8$ MeV. Hence the Freeman 1958 data "anchors" the higher-energy data of Kilian 1969 [9], Cassagnou 1962 [11] and Mani 1964 [12]. This is a serious experimental weakness in the $^7Li(p,\alpha)$ reaction.

Relative error: The relative error is 4% : "... the errors on the relative values at different proton energies are about ±4%." (p. 149 [10])

Normalization error: This is given in Table 1 [10]. Only for the 1.47 MeV measurement can this be calculated to two digits accuracy which is 8.6%. All the other energies are consistent with this normalization error, so this value is assigned. It is said that "... account was taken of the fact that in the lithium reaction two α-particles are emitted per disintegration ..." (p. 149 [10]) Unfortunately it is not clear from this whether a factor of 1/2 is applied at the level of the differential cross-section. To determine how the experimental cross-sections are defined, the datum at 1.01 MeV was compared to the Rolfs 1986 [7] and Engstler 1992 [8] data at about the same energy. From this comparison it is evident the Freeman cross-sections do not include the factor of 1/2.

Cassagnou 1962 [11]: The Saclay data were entered from Fig. 7 (p. 454) of this reference, which includes both Rice and Saclay data. The Rice data were entered previously.

Relative error: "The errors in the total cross-section curve include also the errors quoted in the above references for the energies at which the curves were normalized." (p. 453 [11]) This means that the error bars are larger than they should be if the data was left unnormalized. Unfortunately these effects cannot be disentangled, so that the relative errors in the figure were utilized.

Normalization error: All Saclay data were multiplied by a factor of 10/7 according to the erratum [11]. "The absolute cross-section was obtained by normalizing our curves to the value obtained by Freeman *et al.* at 1.47 MeV and that quoted by Burcham *et al.* at 2.02 MeV" (p. 453 [11]) [The "2.02" MeV should read "2.2" MeV]. Because the absolute cross-section error is not known, it is set to infinity.

Mani 1964 [12]: Data were entered from Fig. 1 (p. 590 [12]) of this reference in the range 3.0 − 10.1 MeV. The proton energies are given in the laboratory system and the cross-section in the CM system: "The conversion ... into the centre-of-mass system ... and the calculation of the total excitation curve." (p. 589 [12])

Relative error: Read from from the error bars in the figure.

Normalization error: "The absolute cross-section was obtained by normalizing to the data of Cassagnou *et al.*" The normalization error is hence set to infinity.

2.6 $^7Li(p,p)$

Bingham 1971 [13]: Elastic data of Ref. [13] were entered. Excited and ground states of ^7Li were separated. The Li target was made out of natural lithium (LiI), but is was possible to distinguish between the ^6Li and ^7Li in the target.

Relative error: The error in the datafile is purely statistical: "With these systematic errors eliminated the errors quoted are cumulative statistical errors only." (p. 268 [13]).

Normalization error: The claim is that normalization errors were eliminated by virtue of calibrating against known cross sections. On p. 267 "The technique of using isotopic abundance ratios and a molecular target, such as LiI, containing an isotope of well-known scattering cross section enables one to achieve small absolute errors by removing the inherent error in dead time corrections, beam integration and solid angle and target thickness determinations. All these errors, which are present in cross section normalization by sequential experiments, were removed in the measurements of the $^6Li(p,p0)^6Li$ and $^7Li(p,p0)^7Li$ absolute cross sections in Table 1." (p. 267 [13]) Because there is only one datum (differential cross section) the normalization is fixed to 1.

Gleyvod 1965 [14]: Elastic differential cross sections as a function of angle for 4.2 MeV protons (Fig. 3 [14]) were entered. The angles and cross sections in Fig. 3 are in the CM frame based on comparison with Fig. 2a, where they are known to be in the CM frame [14]. Ground and excited state ^7Li have been separated. The target is 99.97% ^7Li.

Relative error: "The error in the elastic cross section caused by statistics and background subtraction is between $\pm 2\%$ and $\pm 4\%$ at lower energies and rises to about 8% at the highest energies." (p. 651 [14]) Since the 4.2 MeV data entered are nearer to the lowest energies (range is 2.5-12 MeV), the maximum low energy relative error (4%) was assigned, consistent with the data previously entered by Seamon [15], and consistent with his choice of relative error.

Normalization error: The normalization of the data was done with respect to two other data sets measured by other authors: "The absolute cross section scale was chosen so as to get the best overlap with the low-energy data of Malmberg and of Bashkin and Richards. Malmberg states an accuracy for the absolute cross section of $\pm 10\%$ and Bashkin and Richards $\pm 20\%$. ...we consider our absolute cross section to have an accuracy of about $\pm 15\%$" (p. 651 [14]). Based on this Seamon assigned a normalization error of 15% [15]. Since the the absolute normalization was not measured, the normalization error is here set to infinity. The old normalization error Seamon entered in the datafile was accordingly changed. The measurement in Fig. 3 was at a single energy and various angles [14]: hence one normalization factor.

Kilian 1969 [9]: The energy range of the data [9] is $2.7-10.6$ MeV at angles $40, 60, 70, 80, 90, 110, 120, 130,$ $140, 150, 160$ and 170 degrees. The differential cross-section data in Fig. 3a [9] from $3.1-10.3$ MeV are entered. Ground and excited state ^7Li products are well separated. The target is enriched ^7Li (99.99%).

Relative error: The data that was entered is said to have "Statistische Fehler sind kleiner als die Punkte." (p. 534 [9]). Hence the errors are smaller than the points indicated. The size of the points was estimated and found to be slightly smaller than the EXFOR digitization error, and hence the EXFOR digitization was assigned to the relative error in the datafile (since the data could not directly be read more accurately). The normalizations should be different for each energy. This follows because measurements at the different angles were simultaneously made for a given energy: "Die Messungen wurden mit 16 Halbleiterzählern gleichzeitig durchgeführt, wobei folgende Streuwinkel θ_{Lab} bezetzt waren: ..." (p. 530 [9]).

Normalization error: "...wobei f [the overall normalization] die gemessenen Zählraten an einen absoluten Masβtab anpaβt. Zur Anpassung wurden Messungen im α-Kanal von Mani *et al.* und im Protonenkanal von Fasoli *et al.* benutzt." (p. 535-536 [9]). Consultation of Fasoli *et al.* [16] indicated that that reference also did not estimate its normalization, since it was also fixed to another reference. Based on this we assign an infinite normalization error to the data [9].

2.7 $^7Li(p,n)$

Thornton 1971 [17]: Polarization data with the contribution from the excited state of ^7Be clearly separated, with 6 energies, and between 7 and 8 angles for each energy, are available [17]. One can assume from the plots in Figs. 3 and 4 [17] that this data set is the most extensive in energy and angle up to 1971, and has very small error bars, smaller than previous comparable experiments. This experiment is the state of the art in 1971. The contents of Table 1 [17] was entered. Angles must be converted from the laboratory to the CM frame, but no conversions of the neutron polarizations are necessary.

Relative error: The errors quoted include both statistical and systematic errors, as may be gleaned from "The estimated errors include statistical and background subtraction uncertainties, but not the uncertainty in the analyzing power." (p. 135 [17]) The quoted errors were taken as relative errors.

Normalization error: The uncertainty in the analyzing power is very small: "The statistical uncertainties of the analyzing powers generated by the Monte Carlo nature of PMS [a computer programme] were small." "... uncertainty in MOCCASINS [a computer programme] could be made small." "The statistical uncertainties of the analyzing power caused a negligible uncertainty in the neutron polarizations." "One internal check was made for the analyzing power ... the neutron polarization agreed over the entire angular distribution ..." (p. 138 [17]). Based on this, the normalization uncertainty was first estimated to be 1%, in accordance with Seamon memo [15]. Polarization does not depend on the absolute magnitude of a cross section. A normalization uncertainty of 1% just seems too small given the other data in the datafile. A normalization uncertainty of 4% is implemented similar to other data of the same reaction [50]. Different normalizations can be chosen for each energy based on "Angular distributions were repeated at all energies ..." (p. 134 [17]).

Poppe 1976 [18]: Integrated cross-section data were entered from the upper curve of Fig. 9 of that reference in the energy range $4.25 - 10$ MeV. The magnitude of the cross-sections entered was obtained directly from the experimenters that performed the measurements at LLNL. Fig. 9 contains a missing tick on the y-axis in the printed paper, which can lead one to incorrectly read the cross-section: The correct peak cross-section at 5.0 MeV is 391 mb. The ground and excited products are well separated.

Relative error: Between 4.25 and 12 MeV the data come from the Tandem and between 15.2 and 16 MeV from the Cyclograaff, so that these data sets have different relative errors. The relative error for the Tandem data is 4%: "Major sources of error in the tandem runs are errors in integrating the 5 MeV angular distribution and normalizing to the Macklin and Gibbons measurement, counting statistics, and uncertainty in the variation of detector efficiency from detector to detector and with neutron energy. Background and peak separation errors are relatively minor. Total errors in the tandem relative cross-sections are estimated to be about 4%." (p. 441 [18]) The data has a digitization error associated with their graphical display. The relative error is obtained by adding the 4% error and the digitization error in quadrature. It is said above that the relative error already includes the Macklin and Gibbons normalization, but these is no way to disentangle this.

Normalization error: The normalization is unknown: "These cross sections have been integrated over angle and at 5 MeV the resulting integral was normalized to the absolute measurement of Macklin and Gibbons in order to obtain the absolute differential and total cross sections for each neutron group." (p. 438 [18]) The normalization error is set to infinity. This is because the data of Macklin and Gibbons [19] have been known to be inaccurate: There is no error discussion, and the error on the 5 MeV data point is merely the digitization error.

Elbakr 1972 [20]: The differential cross-section data at 0 degrees were entered from Fig. 1 of that reference. The cross-section was converted from the laboratory to the CM frame.

Relative error: Errors of just over 12% are included. These are both statistical and systematic errors: "Statistical errors are $< 3\%$, while the error on the absolute values is $\pm 12\%$." (p. 521 [20])

Normalization error: The normalization is fixed because the systematic error is already included in the relative error discussed above. A common normalization was assigned for the various energies based on: "The absolute differential cross-sections of the $^7Li(p, n_0)\,^7Be$ and $^7Li(p, n_1)\,^7Be$ reactions were measured at zero degree for proton energies from 2.20 to 5.50 MeV at 0.1 MeV intervals." (p. 519 [20])

2.8 $^7Be(n, p)$

Cervena 1989 [21]: The datum of Ref. [21] was entered. Excited and ground states of ^7Li were not separated [21], but it is known from Koehler's data at the same energy that the excited state only contributes 400 barns [58], while ground state was measured to be 46800 ± 4000 barns [21], so that the excited state disappears in the error. Moreover, it is remarked that "From the measurements performed with thermal neutrons the proton branching ratio was determined to be $\sigma_1/\sigma_0 = (2 \pm 1)\%$" (p. 1266 [21]). Here σ_1/σ_0 is the ratio of the proton branching ratio to the first excited and ground states of ^7Li. The target ^7Be was pure ^7Be, but with a boron admixture, although "The adverse effects of the boron admixture were completely eliminated." [21]

Relative error: "The given error (standard deviation) was due to a statistical error (1%) and several systematic errors among which the most important are uncertainty in the number of ^7Be atoms (5%), uncertainty in the number of LiI atoms (5%), uncertain knowledge of measuring geometry and possible variation of neutron flux (5%)." (p. 1266 [21])

Normalization error: Because there is only one datum the normalization is fixed to 1.

2.9 $^7Be(n, \alpha)$

A search for data on this reaction yielded only an upper bound on a cross-section, which was not incorporated.

2.10 $^7Be(n, d)$, $^7Be(n, n)$, $^7Li(p, d)$

A search for data in these reactions below the maximum excitation energy of this analysis (26 MeV) was performed. No data were found.

2.11 $^6Li(d, \alpha)$

In this reaction a detailed analysis was made of the normalizations of data sets that were entered before 2002, because of an ambiguity of a factor of 1/2 in the cross-section due to identical particles in the final state. During this investigation information about normalization errors was also incorporated.

Engstler 1992 [8]: The data, which were entered previously, were reanalyzed. It appears that the entered data are the S-factor in Table 1 [8] converted to the cross-section.

Relative error: The entered data appear to include both the error quoted in Table 1 [8] and the error quoted in the footnotes, which should be construed as a normalization error.

Normalization error: In the light of the preceding discussion, there is no further need for an explicit normalization error. The normalization is hence fixed. The normalization for a certain part of the data was determined in this work: "The absolute cross-sections $\sigma(E)$ were determined at the effective energies from $E = 32$ to 1004 keV (400 kV and 4 MV accelerators) using ..." (p. 478 [8]) The normalization for another part of the data was determined in a previous work: "... the absolute scales of the solid target data have been normalized to previous results using polynomial fits." (p. 480 [8]) The differential data that were previously entered from Fig. 5 [8] are in relative units and have an infinite normalization error. It is explicit in Eq. 3 [8] that a factor of 1/2 was included in the cross-section definition.

Elwyn 1977 [22]: The data, which were entered previously, were reanalyzed. The integrated cross-sections are reported in Fig. 5 [22].

Relative error: Errors quoted in Fig. 5 [22] and entered in the datafile only include relative errors: "The relative precision of the present results is indicated by the error bars." (caption of Fig. 5 [22]) This can be verified from the total relative error quoted in Table II [22].

Normalization error: The total error is $8.5 - 10\%$. The maximum value of 10% is implemented. It appears that the cross-section was already multiplied by a factor of 1/2: "Figure 5 shows the reaction cross-sections obtained in the present experiment compared to previous low-energy measurements. The disagreement of about a factor of 2 with the results of Refs. 3 and 7 at the energies above 0.5 MeV seems to reflect in part the confusion in the definition of the cross-section being reported in these papers." (p. 1751 [22])

Bertrand 1968 [23]: The data, which were entered previously, were reanalyzed. The data are said by Elwyn 1977 [22] not to have the factor of 1/2 in the cross-section definition: "Figure 5 shows the reaction cross-sections obtained in the present experiment compared to previous low-energy measurements. The disagreement of about a factor of 2 with the results of Refs. 3 and 7 at the energies above 0.5 MeV seem to reflect in part the confusion in the definition of the cross-section being reported in these papers." (p. 1751 [22]) Ref. 3 mentioned here is Bertrand 1968 [23].

Golovkov 1981 [24]: The data, which were entered previously, were reanalyzed. The data do appear to have the factor of 1/2 in the cross-section definition, according to Fig. 1b and Fig. 9 of Engstler 1992 [8].

McClenahan 1975 [25]: Integrated cross-section data of from $0.4-3.5$ MeV are available, and were from entered Fig. 9 of that reference.

Relative error: There are no error bars on Fig. 9 [25]. Hence each point is treated as though its relative error is the normalization error of 15% discussed below.

Normalization error: The absolute normalization is measured: "Therefore, it is concluded that the over-all uncertainty in the absolute cross-sections reported here is no more than 15%." (p. 373 [25]) Because the relative error is already set equal to 15%, the normalization is fixed. The McClenahan 1975 data "anchors" the Gould 1975 data [26] discussed below, since the latter is higher in energy and free to float but overlaps with the McClenahan [25] data. The McClenahan 1975 [25] data are said by Elwyn 1977 [22] to have the factor of 1/2 in the cross-section definition.

Gould 1975 [26]: Integrated cross-section data were entered based on Fig. 5 of that reference. Although data from $2.2 - 5.9$ MeV are available, only data up to 4.9 MeV were entered.

Relative error: "We estimate the uncertainty in our cross section results to be $\sim 15\%$." (p. 699 [26]) The relative error is assigned to be 15%.

Normalization error: The absolute normalization is not measured: "... we used as our reference cross-section the value of Ref. 1 quoted for $^6Li(d,d)$ at 8 MeV bombarding energy and angle of 70 degrees." (p. 699 [26]) Ref. 1 is J. Rand McNally, Jr., 1973. Based on this the normalization error is set to infinity. Comparison with Fig. 1 [26] indicates that the choice of a factor of 1/2 is the same as McClenahan 1975 [25].

Cai 1985 [27]: Integrated cross-section data were entered. The reference is not accessible so data from EXFOR were directly entered.

Relative error: The errors on the data points are said by EXFOR to include "Statistical error, uncertainty of target nuclide number, uncertainty of solid angle." Hence the errors include both relative and normalization errors.

Normalization error: Because the relative error already includes the normalization error, the normalization is fixed.

Risler 1977 [28]: Data from $1.0 - 11.5$ MeV are available for 15 energies, although only data up to 5.0 MeV were entered. The data entered are based on the differential cross sections in Fig. 1 [28] and integrated cross-sections in Fig. 2 [28].

Relative error: For the differential cross-sections "... the statistical errors are smaller than the dots." (p. 118 [28]) Hence the EXFOR value of 0.5 mb is taken (I estimate 0.7 mb). For the integrated cross-section no errors are stated and it is assumed that the points again signify the errors. The EXFOR value is 0.05 mb $\times\, 4\pi = 0.7$ mb. My estimate is 1.3 mb which is entered.

Normalization error: The absolute normalization error is not given, although it is stated that "The uncertainty of the thickness and therefore also the error in the absolute values of the differential cross-section is approximately 20%." (p. 118 [28]) Based on this the normalization error is set to 20%.

In the discussion of the differential cross-section the following is stated about the factor of 1/2 in the cross-section: "The fact that identical particles are emitted from the reaction under investigation was taken into account for the calculation of the cross-section." (p. 118 [28]) The comparison of the integrated cross-sections in Fig. 2 [28] with those of McClenahan 1975 [25] indicates that these two references use the same convention for the factor. Also, it is evident from the numerical values that if a factor of 1/2 was included for the differential cross-sections, then it was also included for the integrated cross-sections. This is all consistent with taking Risler 1977 [28] to include the factor of 1/2 *both* for the differential and integrated cross-sections.

Jeronymo 1962 [29]: The integrated and differential data are from ~ 1 to ~ 5 MeV, and have been entered. Integrated data originate from Fig. 4 (p. 13 [29]), and differential data from Fig. 2 (p. 12 [29])

Relative error: Both Figs. 2 and 4 [29] show relative errors, the size of which is consistent with the magnitude stated in the text for the data in Fig. 1 [29]: "The points on the curve have a total error of 5% which comprises the counting statistics of the detector and the monitor and the experimental errors in the charge measurement, fluctuations in the electronics, etc." (p. 12 [29])

Normalization error: There is no normalization error stated in the text, and it is hence set to infinity (the integrated data are claimed to be cross-sections, while the differential data are stated to have no absolute normalization). Since the normalization error is set to infinity, it is not important whether there is a factor of 1/2 or not in the cross-sections. A different normalization is chosen for each energy for which differential data are entered: "Excitation curves for 12 angles from 85^o to 165^o in the laboratory system were obtained using solid state counters to detect the α particles emitted from the reactions." (p. 11 [29])

2.12 $^6Li(d,p)$

McClenahan 1975 [25]: Integrated cross-section data of from $0.5-3.4$ MeV are available, and were entered from Fig. 14 of that reference. Ground and excited ^7Li products are separated.

Relative error: There are no error bars on Fig. 14 [25], but "Where no error bar is shown, the statistical uncertainty is comparable to or smaller than the size of the point." (p. 381 [25]) The EXFOR digitization error of 0.3 mb is found to be smaller than the size of the points I estimated, so that the relative error is taken to be 1.0 mb.

Normalization error: The absolute normalization is measured: "Therefore, it is concluded that the over-all uncertainty in the absolute cross-sections reported here is no more than 15%." (p. 373 [25]) Based on this the normalization error is set to 15%. The McClenahan 1975 [25] data "anchors" the Gould 1975 [26] data discussed below, since the latter is higher in energy and free to float but overlaps with the McClenahan data.

Gould 1975 [26]: Integrated cross-section data were entered based on Fig. 5 of that reference. Although data from $2.3-7.0$ MeV are available, only data up to 5.0 MeV were entered. Ground and excited ^7Li products are separated.

Relative error: "We estimate the uncertainty in our cross section results to be $\sim 15\%$." (p. 699 [26]) The relative error is assigned to be 15%.

Normalization error: The absolute normalization is not measured: "... we used as our reference cross-section the value of Ref. 1 quoted for $^6Li(d,d)$ at 8 MeV bombarding energy and angle of 70 degrees." (p. 699 [26]) Ref. 1 is J. Rand McNally, Jr., 1973. Based on this the normalization error is set to infinity.

Cai 1985 [27]: Integrated cross-section data were entered. The reference is not accessible so data from EXFOR were directly entered.

Relative error: The errors on the data points are said by EXFOR to include "Statistical error, uncertainty of target nuclide number, uncertainty of solid angle." Hence the errors include both relative and normalization errors.

Normalization error: Because the relative error already includes the normalization error, the normalization is fixed.

Bruno 1966 [30]: Differential cross-section data, available in the energy range $1.0 - 2.0$ MeV, were entered from Fig. 5 of that reference. The angles were measured in the CM frame: "Les distributions angulaires des protons p_0 et p_1 sont données dans le système du centre de masse pour le mêmes valeurs d'angles et d'énergie que pour les alphas." (p. 519 [30]) Ground and excited products are well separated.

Relative error: The relative errors were entered from Fig. 5 [30] where available. For points where errors are not indicated, errors of 0.27 mb were assigned, since this is the error corresponding to the differing cross-sections obtained for points that are essentially at the same energy.

Normalization error: No normalization error is discussed, and it is hence set to infinity.

Durr 1968 [31]: Differential cross-section data are available in the energy range $2.1 - 10.9$ MeV at angles $20, 30, 40, 50, 60, 70$ and 80 degrees, and were entered up to 4.8 MeV from Fig. 2 of that reference. The angles were converted from the laboratory to the CM frame. Ground and excited products are well separated: "... die Protonen p_0 and p_1 stets energetisch von anderen deuteroneninduzierten Reaktionkanälen separiert liegen." (p. 156 [31])

Relative error: The data that was entered are said to have "Die eingetragenen Punkte und Fehler enthalten nur den statistishen Fehler." (p. 156 [31]) "Die Durchmesser der Punkte, sowie die Fehlenbalken sind mittlere statistiche Fehler." (p. 155 [31]) Hence the errors are the size of the points if not indicated. For angles $20, 30, 40, 50$ and 60 degrees only points are indicated. It seems impossible that the statistical errors are that small, and in addition, the Ph.D. thesis corresponding to the paper states: "Der Statistische Fehler lag bei allen angegebenen Werten zwischen 0.1 und 0.2 mb/sr." (p. 29) Hence relative errors on the $20, 30, 40, 50$ and 60 degree points are assigned to be 0.2 mb/sr. The relative errors on the 70 and 80 degree points are assigned as in Fig. 2 [31].

Consultation with the Ph.D. thesis indicates that the measurements were taken at specific energies, and that for each energy the measurements were taken at $20, 30, 40, 50, 60, 70$ and

80 degrees. The values of these energies are read from the thesis, and the values of the differential cross-section and error on the cross-section are read from EXFOR. However, the table on p. 29 of thesis gives the actual numerical values of these differential cross-sections for the points from 4.4 MeV onwards. These values are entered instead of the EXFOR values digitized from Fig. 2 [31].

Normalization error: Normalization is fixed relative to another reference: “Die bekannten Messugen (Ref. 15) wurden zur Anpassung der Wirkungsquerschnitte benutzt.” (p. 159 [31]) Based on this we assign an infinite normalization error.

2.13 $^6Li(d,n)$

McClenahan 1975 [25]: Integrated cross-sections from $0.5-2.9$ MeV are available, and were entered based on Fig. 16 of that reference. Ground and excited ^7Li products are separated.

Relative error: The error bars on Fig. 16 [25] are only part of the relative error: “The error bars represent statistical uncertainties, which include the uncertainty in determining the background.” (p. 381 [25]) This is because a symmetry relation is used with is not entirely accurate: “Because of charge symmetry, one would expect the ratio of the (d,p_0) to the (d,p_1) reaction cross-sections to be similar to the ratio of the (d,n_0) to the (d,n_1) reaction cross sections. This has been shown experimentally to be true over the energy range $0.4-3.3$ MeV to an accuracy varying from 3% at 3 MeV to 12% at 0.5 MeV.” (p. 381 [25]) The error due to the symmetry relation was linearly interpolated between 12% and 3%, and was added to the error given in Fig. 16 [25] in quadrature. The result is entered as the total relative error.

Normalization error: The absolute normalization is measured: “Therefore, it is concluded that the over-all uncertainty in the absolute cross-sections reported here is no more than 15%.” (p. 373 [25]) Based on this the normalization error is set to 15%.

Thomason 1970 [32]: The energy range of the polarization data is $2.5-3.7$ MeV, which were entered from Fig. 2 of that reference. Ground and excited products are well separated.

Relative error and normalization error: The errors include both relative and normalization errors: “The error bars include statistical errors from the accidental coincidence background subtraction and also from the tails of the adjacent peaks. Also included is an uncertainty to allow for a change in the calculated asymmetry at each point that results from a change in the cross-section ratio by 25% for the three lowest energies, and 50% for the two highest energies.” (p. 662 [32]) “This ratio was obtained from the $^6Li(d,n_0)$ and $^6Li(d,n_1)$ relative differential cross-section measurements at 2.9 MeV by Birk *et al.* and at 2.56 and 3.08 MeV by Cranberg *et al.*” (p. 661 [32]) These errors are incorporated as the relative error. The normalization is hence fixed.

2.14 $^6Li(d,d)$

Abramovich 1976 [33]: The energy range of the differential data is $3-10$ MeV, and data up to 5 MeV were entered. These data correspond to the data of Fig. 1 [33], although the data entered were supplied by the authors [33] to EXFOR. Ground and excited products are well separated.

Relative error: "The error of relative values of angular distribution does not exceed 5 per cent." (p. 843 [33]) This error is composed of the following errors: "Relative error of the angular distribution includes statistical error and random error of peak-area (as a rule this error does not exceed 4 per cent). An error is likely to exist related to inaccurate geometry reproducing an inaccurate angular measurement (about 3 per cent)." (p. 843 [33])

Normalization error: This is set to infinity because the normalization is fixed from Ref. 1 in the paper (p. 843 [33]): "The angular distributions of the elastically scattered deuterons were converted to absolute values on the basis of the data of [1]." (p. 843 [33]) Normalizations are taken to be the different for a each energy: "A broad angular range was spanned by rotating the detector disk through angles ..." (p. 843 [33])

Table 2 contains a complete list of the data in the ^8Be analysis.

3 Fitting procedure

In the 2002 analysis the initial particles in $^4He(\alpha, X)$ were allowed to be in relative S- , D- , G- and I-waves, and those in the $^7Li(p,X)$, $^7Be(n,X)$ and $^6Li(d,X)$ in the S- and P-waves. When new data in the reactions $^7Li(p,X)$ were added, the laboratory energy of the proton was greatly increased, so that the possibility of at least D-waves needed to be included. Henceforth D-waves were added in both the $p\,^7Li$ and $n\,^7Be$ channels. The effect of the inclusion of D-waves was found to be important, as is discussed below. Subsequently, F-waves were added in the $p\,^7Li$ and $n\,^7Be$ channels, as well as L-waves in $\alpha\,^4He$, and D-waves in $d\,^6Li$. The inclusion of these waves did not seem to change the qualitative features of the fit, indicating that the former number of waves successfully parameterized the data. The number of parameters (R-matrix resonance energies and reduced widths) increased from ~ 60 to ~ 140 due to inclusion of the new waves since 2002.

Allowance was made for the radius of the $d\,^6Li$ channel to change, because of certain pathologies in the fit. The value of this channel radius changed from 6.50 fm to 6.46 fm. It hence appears that these pathologies cannot be explained by the radius. The radius for the $\alpha\,^4He$ channel is 4 fm, and for the $p\,^7Li$ and $n\,^7Be$ channels 3 fm.

The current analysis is the most comprehensive ever performed for the ^8Be system with ~ 4700 data points. The $\chi^2/(\text{point})$ is listed for each reaction in Table 3. The overall χ^2 per degree of freedom $= 7.9$ is identical in the 2002 and 2004 analyses. It is found that the code

Reaction	Data Ref.	E (MeV)	Data Ref.	E (MeV)
$^4He(\alpha,\alpha)$	Heydenburg 1956 [34]	$0.6-3.0$	Phillips 1955 [35]	$3.0-5.8$
	Tombrello 1963 [36]	$3.8-11.9$	Steigert 1953 [37]	$12.9-20.4$
	Chien 1974 [38]	$18.0-29.5$	Mather 1951 [39]	20.0
	Nilson 1956 [40]	$12.3-22.9$	Briggs 1953 [41]	$21.8-22.9$
	Bredin 1959 [3]	$23.1-38.4$	Graves 1951 [42]	30.0
$^4He(\alpha,p)$	King 1977 [4]	$39.0-49.5$		
$^4He(\alpha,d)$	King 1977 [4]	$46.7-49.5$		
$^7Li(p,\alpha)$	Spraker 2000 [5]	$0.0-0.1$	Harmon 1989 [6]	$0.0-0.3$
	Rolfs 1986 [7]	$0.0-1.0$	Engstler 1992 [8]	$0.0-1.3$
	Cassagnou 1962 [11]	$1.4-4.8$	Kilian 1969 [9]	$3.4-9.4$
	Freeman 1958 [10]	$1.0-1.5$	Mani 1964 [12]	$3.0-10.1$
$^7Li(p,p)$	Warters 1953 [43]	$0.4-1.4$	Bardolle 1966 [44]	$0.8-2.0$
	Lerner 1969 [45]	1.4	Malmberg 1956 [46]	$1.3-3.0$
	Gleyvod 1965 [14]	$2.5-4.2$	Brown 1973 [47]	$0.7-2.4$
	Bingham 1971 [13]	6.9	Kilian 1969 [9]	$3.1-10.3$
$^7Li(p,n)$	Macklin 1958 [19, 48]	$1.9-3.0$	Barr 1978 [49]	$2.0-3.0$
	Burke 1974 [50]	$1.9-3.0$	Meadows 1972 [51]	$1.9-3.0$
	Elbakr 1972 [20]	$2.2-5.5$	Darden 1961 [52]	$2.0-2.3$
	Austin 1961 [53]	$2.1-3.0$	Elwyn 1961 [54]	$2.0-2.6$
	Baicker 1960 [55]	3.0	Andress 1965 [56]	3.0
	Hardekopf 1971 [57]	3.0	Thornton 1971 [17]	$3.0-5.5$
	Poppe 1976 [18]	$4.3-10.0$		
$^7Be(n,p)$	Koehler 1988 [58]	$0.0-0.0$	Cervena 1989 [21]	0.0
$^6Li(d,\alpha)$	Engstler 1992 [8]	$0.0-1.3$	Golovkov 1981 [24]	$0.1-0.1$
	Elwyn 1977 [22]	$0.1-1.0$	Bertrand 1968 [23]	$0.3-1.0$
	Cai 1985 [27]	$0.5-2.5$	McClenahan 1975 [25]	$0.5-3.4$
	Jeronymo 1962 [29]	$0.9-5.0$	Gould 1975 [26]	$2.2-4.9$
	Risler 1977 [28]	$1.0-5.0$		
$^6Li(d,p)$	Szabo 1982 [59]	$0.1-0.2$	Body 1979 [60]	$0.1-0.2$
	Bertrand 1968 [23]	$0.3-1.0$	Elwyn 1977 [22]	$0.1-1.0$
	Cai 1985 [27]	$0.5-2.5$	McClenahan 1975 [25]	$0.5-3.4$
	Bruno 1966 [30]	$1.0-2.0$	Gould 1975 [26]	$2.3-5.0$
	Durr 1968 [31]	$2.1-4.8$		
$^6Li(d,n)$	Hirst 1954 [61]	$0.1-0.3$	McClenahan 1975 [25]	$0.5-2.9$
	Szabo 1977 [62]	$0.1-0.2$	Haouat 1985 [63]	$0.2-1.0$
	Elwyn 1977 [22]	$0.2-0.9$	Bochkarev 1994 [64]	0.8
	Thomason 1970 [32]	$2.5-3.7$		
$^6Li(d,d)$	Abramovich 1976 [33]	$3.0-5.0$		

Table 2: Data in the ^8Be analysis. The laboratory energy of the projectile is E.

Reaction	χ^2/p	Reaction	χ^2/point	Reaction	χ^2/point
$^4He(\alpha,\alpha)$	19.0	$^7Li(p,\alpha)$	7.5	$^6Li(d,\alpha)$	1.6
$^4He(\alpha,p)$	7.7	$^7Li(p,p)$	5.7	$^6Li(d,p)$	3.0
$^4He(\alpha,d)$	6.5	$^7Li(p,n)$	2.7	$^6Li(d,n)$	2.1
		$^7Be(n,p)$	0.6	$^6Li(d,d)$	56.1

Table 3: χ^2 / (data point) for the various reactions.

identifies certain data sets that are difficult to fit, particularly in the reactions $^4He(\alpha,\alpha)$ and $^6Li(d,d)$. In some cases these have been identified with old data on $\alpha\, ^4He$ elastic scattering where the original publications appear to underestimate the relative errors, so that the data is considerably more unreliable than it would appear. It was demonstrated before that certain data points are demonstrably in error [65], casting doubt on the reliability of the entire data set.

The fit is found to be robust, in the sense that it is not driven by bad data. This was established by eliminating all data points that fit with more than 3 standard deviations: this changed the χ^2/(d.o.f) to only 1.5, indicating that the high χ^2 of the fit is partially due to poor data. It is found that 33% of the data points in the $\alpha\, ^4He$ elastic scattering were discarded, while less than 19% of points were discarded for all other reactions, indicating that $\alpha\, ^4He$ elastic scattering contains poor data. The resonance structure with and without the rejected data points is found to be the same, indicating that it is robust under change of inclusion of data points.

4 Resonance content

After allowing for the possibility of D-waves in the $n\, ^7Be$ and $p\, ^7Li$ systems, the χ^2/(d.o.f.) improved dramatically, but the EDA code [66] rejected the $J^\pi T = 1^-0$ level. Here J is the total angular momentum, π the parity and T the isospin of the level. This level used to have an S-matrix energy of 18.66 MeV and S-matrix width of 157 keV in the 2002 analysis, with no corresponding experimental level. The code preferred the a 2^-0 level at a similar mass, which has a corresponding experimental level, to the old 1^-0 level, and completely rejected the 1^-0 level.

The physics content of the evaluation was found by calculating the S-matrix energies and widths of the resonances, displayed in Table 4. These resonances should be compared to the "experimental" resonances believed to exist on the basis of a summary of resonances found in experimental data and other analyses [67]. A comparison with experiment indicates substantial agreement, indicating that the R-matrix evaluation is indeed based on the correct physics input. Most of the resonances found in the R-matrix evaluation correspond

$J^\pi T$	Energy (MeV)			Width (keV)		
	2002	2004	Experiment	2002	2004	Experiment
0^+0	-0.08	-0.06	0	0	0	$(6.8 \pm 1.7) \times 10^{-3}$
		20.13	20.2		1044	720 ± 20
2^+0	2.79	2.78	3.06 ± 0.03	1395	1197	1370 ± 70
	11.65	16.57	≈ 9	19688	18883	-
	17.00		16.922 ± 0.003	5		74.0 ± 0.4
		20.08	20.1		781	880 ± 20
		22.17	22.2		723	≈ 800
		25.06	25.2		1961	-
4^+0	11.69	11.56	11.35 ± 0.15	4174	4405	≈ 3500
		24.03	25.5		3420	broad
2^-0	17.92	18.38	18.91	2250	1945	122
3^+0	19.23	19.23	19.24	197	172	227 ± 16
3^+1	19.05	19.03	19.07	323	282	270 ± 20
1^+0	18.16	18.16	18.150 ± 0.004	136	141	138 ± 6
1^+1	17.66		17.640 ± 0.001	13		10.7 ± 0.5
4^-0		21.37	20.9		981	1600 ± 200
3^-0		21.62	21.5		1087	1000
1^-1		21.50	19.40		1247	≈ 645

Table 4: Comparison of R-matrix (2002 [65] and 2004 analyses) and "experimental" [67] energies and widths of ^8Be resonances. A blank entry in a R-matrix column means that there is no resonance corresponding to the experimental resonance in the R-matrix analysis. Energies are relative to the ^8Be ground state. The very broad 2^+0 resonance may not be a real resonance.

to resonances known experimentally.

The narrow ground state 0^+0 resonance parameters do not agree perfectly with experiment since there is no low-energy $^4He(\alpha,\alpha)$ data in the datafile at the same excitation energy as the resonance mass. The experimental $J^\pi T = 4^-?$ peak is tentatively identified with the 4^-0 peak found in this analysis. The possibility that the peak has isospin 1 was not investigated. The quantum numbers of the peak at 21.5 MeV in the $^7Li(p,n)$ reaction is experimentally [67] thought to be $J^\pi T = 3^??$, with the parity possibly positive. Our fits prefers the quantum numbers $J^\pi T = 3^-0$, having allowed for all the parity and isospin possibilities.

The exceptions to the substantial agreement between the R-matrix analysis and experiment in Table 4 are: The ~ 18 MeV 2^-0 resonance does not agree well in width, and the ~ 21 MeV 1^-1 resonance does not agree well in mass. (The latter resonance is not experimentally known to be isospin 1). Since the R-matrix evaluation contains more data than any known analysis, the experimental masses and widths may well be in doubt [1], although this is less likely for narrow experimental resonances.

Except for the two narrow experimental resonances not found in the 2004 analysis indicated in Table 4, the following experimental resonances are not found in the analysis: A 2^+ $(0+1)$ resonance at 16.626 ± 0.003 MeV with width 108.1 ± 0.5 keV, a 4^+0 resonance at 19.86 ± 0.05 with width 700 ± 100 keV, a 1^-1 resonance at 22.0 MeV with width ≈ 4000 keV, a $(1,2)^-1$ resonance at 24.0 MeV with width ≈ 7000 keV, and three resonances in the region $22-23$ MeV with widths $50-340$ keV with unknown $J^\pi T$. (The latter may be associated with the 5^+0 resonance described below).

There are some resonances found in the 2004 R-matrix analysis, which were not found in the 2002 analysis, and have no experimental analogues: a 22.97 MeV 2^+0 resonance with width 1616 keV, a 20.32 MeV 8^+0 resonance with width 482 keV, and a 22.54 MeV 5^+0 resonance with width 232 keV. These resonances have a "strength" parameter within 1% of 1, which indicates that they probably are real new resonances. The 22.97 MeV 2^+0 resonance is near to the 22.17 MeV resonance with the same quantum numbers in Table 4. The 22.97 MeV resonance fits the peak observed around 1 MeV d laboratory energy in the $^6Li(d,X)$ reactions. On the other hand, the 22.17 MeV resonance fits the peak at around 6 MeV p laboratory energy in the $^6Li(p,\alpha)$, and around 45 MeV α laboratory energy in the time-inverse $^4He(\alpha,p)$ reactions. Although it is conceivable that all these peaks can be fitted with just one 2^+0 resonance, with the $d\,^6Li$ threshold at 22.28 MeV, the current fit prefers two resonances. There is possibly the need for at least one 1^+ resonance near 21 MeV with a strength within 6% of 1. The current fit has a 1^+1 resonance at 20.44 MeV with width 663 keV, and a 1^+0 resonance at 21.45 MeV with width 620 keV. Together with the other resonances in Table 4, there are 19 resonances in the 2004 analysis, while there were only 10 resonances in the 2002 analysis.

5 Cross-sections

Cross-sections for the $^4He(\alpha,p)$, $^4He(\alpha,d)$, $^7Li(p,\alpha)$, $^7Li(p,n)$, $^6Li(d,\alpha)$, $^6Li(d,p)$ and $^6Li(d,n)$ reactions in the energy range corresponding to the excitation energy of this analysis (26 MeV) are shown in Figs. 1-8. The laboratory energies up to which data were previously entered are indicated in Table 1. Experimental cross-section data that are part of the R-matrix fit are indicated.

The $^4He(\alpha,p)$ (Fig. 1) and its time-inverse reaction, $^7Li(p,\alpha)$ (Fig. 3), clearly show two resonance peaks. The low-energy peak corresponds to the 0^+0 and 2^+0 resonances at 20 MeV (the 2^+0 resonance is dominant [68]), and the high-energy peak to the two 2^+0 resonances at 22 and 23 MeV. The shape of the $^4He(\alpha,p)$ reaction is driven by the $^7Li(p,\alpha)$ reaction, which has much more data.

Figure 1: The $^4He(\alpha, p)$ cross-section. Experimental data are from King [4].

Figure 2: The $^4He(\alpha, d)$ cross-section. Experimental data are from King [4].

The $^4He(\alpha, d)$ (Fig. 2) and its time-inverse reaction, $^6Li(d, \alpha)$ (Fig. 6), show two resonance peaks. The low-energy peak is the 2^+0 resonance at 23 MeV, and the high-energy peak is the 4^+0 resonance at 24 MeV and the 2^+0 resonance at 25 MeV. The shape of the $^4He(\alpha, d)$ reaction is driven by the $^6Li(d, \alpha)$ reaction, which has much more data.

The $^7Li(p, n)$ reaction in Fig. 4 shows three peaks. The low-energy peak is due to the 3^+0 and 3^+1 resonances at 19 MeV. The medium-energy peak arises from the 3^-0 resonance at 22 MeV, and possibly also from the 4^-0 resonance at 21 MeV and the 1^-1 resonance at 22 MeV. The high-energy peak is due to the two 2^+0 resonances at 22 and 23 MeV. These resonances can be seen as peaks in all reactions shown in Figs. 1-8. The high-energy peak appears to be required in addition to the resonances associated with the medium-energy peak, as an attempt to eliminate the high-energy peak has failed. The data that require the high-energy peak could be the Thornton 1971 [17] polarization data at 5.5 MeV p laboratory energy, or even the Kilian 1969 [9] differential data at 6.2 MeV p laboratory energy in the $^7Li(p, p)$ reaction. This reaction is related to $^7Li(p, n)$ by isospin symmetry. The magnitude and shape of the $^7Li(p, n)$ cross section from $3 - 7$ MeV have changed considerably at various stages of the analysis, so that further investigation of this reaction is needed.

The $^6Li(d, \alpha)$, $^6Li(d, p)$ and $^6Li(d, n)$ reactions in Figs. 6-8 all mandate the low-energy peak associated with the 2^+0 resonance at 23 MeV. Furthermore, the $^6Li(d, \alpha)$ and $^6Li(d, p)$ reactions mandate a broad high-energy peak associated with the 4^+0 resonance at 24 MeV and the 2^+0 resonance at 25 MeV. The similar form of the $^6Li(d, p)$ and $^6Li(d, n)$ cross-sections are noticeable: the isospin 0 components of these reactions are related by isospin symmetry. Less data is available for the $^6Li(d, n)$ reaction, compared with $^6Li(d, p)$. The $^6Li(d, n)$ reaction is hence constrained by $^6Li(d, p)$.

6 Evaluated and Maxwellian averaged cross-sections

Evaluated cross-section files in ENDF format were prepared for the twelve reactions $p\,^7Li$, n^7Be, $d^6Li \rightarrow \alpha^4He$, p^7Li, n^7Be, d^6Li. Maxwellian averaged cross-sections in NDI format were prepared for the six reactions $^7Li(p, \alpha)$, $^7Li(p, n)$, $^7Be(n, p)$, $^6Li(d, \alpha)$, $^6Li(d, p)$ and $^6Li(d, n)$.

Figure 3: The $^7Li(p,\alpha)$ cross-section. Experimental data are from Spraker [5], Harmon [6], Rolfs [7], Engstler [8], Rice [11], Saclay [11] and Mani [12].

Figure 4: The $^7Li(p,n)$ cross-section. Experimental data are from Macklin [48], Barr [49] and Poppe [18].

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Figure 5: The $^7Be(n,p)$ cross-section. Experimental data are from Cervena [21] and Koehler [58].

Figure 6: The $^6Li(d,\alpha)$ cross-section. Experimental data are from Engstler [8], Golovkov [24], Elwyn [22], Bertrand [23], Cai [27], McClenahan [25], Jeronymo [29], Gould [26] and Risler [28].

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Figure 7: The $^6Li(d,p)$ cross-section. Experimental data are from Szabo [59], Body [60], Bertrand [23], Cai [27], Elwyn [22], Bruno [30], McClenahan [25] and Gould [26].

Figure 8: The $^6Li(d,n)$ cross-section. Experimental data are from Hirst [61], McClenahan [25], Szabo [62], Haouat [63] and Elwyn [22].

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